



# Selective oxidation of alkylarenes to aromatic acids/ketone in water by using reusable binaphthyl stabilized Pt nanoparticles (Pt-BNP) as catalyst

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## ABSTRACT

An efficient methodology for the selective and controlled oxidation of petroleum waste methylarenes/alkylarenes to aromatic carboxylic acids/ketone using easily recoverable and recyclable binaphthyl stabilized Pt nanoparticles (Pt-BNP) as a catalyst has been developed. The greener oxidant *aq. tert*-butyl hydroperoxide (TBHP) and green solvent water have been utilized in this oxidation reaction. The methodology is well tolerated with different functional groups. The less reactive electron deficient toluenes are also oxidized by Pt-BNP and gave a good yield of corresponding carboxylic acids with a high turnover number (TON) 738–1448. The Pt-BNP catalyst was recovered and reused up to five catalytic cycles. The heterogeneous test suggested that the reaction is catalyzed by heterogeneous Pt-BNP catalysts. Based on control experiments and literature reports, a possible reaction mechanism has been proposed.

## 1. Introduction

Selective oxidation of aromatic hydrocarbons is highly important in both academia and industry [1–6]. From economic as well as environmental point of view, oxidation of hazardous petroleum by-product such as toluene and volatile organic compounds (VOCs) to other useful chemicals is gaining more interest [7–12]. The unselective oxidation of toluene gives a mixture of oxidized products including benzyl alcohol, benzaldehyde, benzoic acid, benzoate ester and phenol [13–15]. Benzoic acid, and its sodium and potassium salts are used as food preservative materials. Also, it has high demand in chemical, pharmaceutical, and agricultural industries as carboxylic acid moiety can be easily converted into other functional groups such as amide, ester, acid chloride, alcohol, iodide etc. by a simple chemical operation [16–20].

Due to the high demand of benzoic acid, the attention is being drawn towards the synthesis of benzoic acid from different types of readily available chemicals such as benzyl alcohol, benzaldehyde, benzoic acid chloride, benzamide, benzoate esters, benzonitrile, toluene, etc. [21–27]. Among all, the synthesis of benzoic acid from naturally abundant toluene is in high demand till date [28–30]. In industry, toluene is oxidized to benzoic acid in the presence of homogeneous catalysts at high temperature and pressure. The most common method is “Dow toluene air oxidation process.” In this process, soluble

cobalt naphthenate catalyst is used for oxidation of toluene in air under 40–70 psi pressure at 150 °C [31]. Another popular method in the industry for the synthesis of commercial benzoic acid is the use of homogeneous cobalt acetate catalyst at high temperature and pressure of molecular oxygen and bromide as a promoter with acetic acid as solvent [32–34]. Use of acetic acid as solvent and bromide as promoter creates difficulty in separation of product and catalyst. Also, a large volume of toxic waste is produced, making this process environmentally and economically unfavourable.

Therefore, many attempts were made to oxidize toluene in vapour phase condition in presence of a solid catalyst to make an environmentally benign process (See SI, Table S1) [35–38]. The use of liquid phase oxidation process has advantages such as easy operation and achieving high selectivity under mild reaction conditions. Many efforts have been made to improve the efficiency of oxidation of toluene in the liquid phase using a homogeneous catalytic system in a volatile organic solvent [38–41]. However, greater selectivity is observed when the conversion is low; when the conversion is high, over-oxidation to CO<sub>2</sub> and other by-products have been observed [42–45]. Thus, there is a need to develop a selective oxidation reaction that avoids over-oxidation and side-products formation, where naturally abundant greener solvent such as water can be used as a solvent under mild reaction condition making it an environmentally benign process.

Recently, the use of the heterogeneous catalyst has shown several

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<sup>1</sup> Dedicated to Padma Shri Prof. Vinod K. Singh on the occasion of his 60th birthday

advantages over a homogeneous catalyst, as it can be easily recovered from the reaction mixture and reused for several catalytic cycles [46–49]. Recently, several attempts have been employed for the oxidation of toluene with environment-friendly oxidants such as TBHP,  $\text{H}_2\text{O}_2$  or molecular oxygen with heterogeneous transition metal or metal oxide catalyst in replacement of their homogeneous counterparts [50–55] (Also see SI, Table S1). However, most of the catalysts showed poor turn over number (TON) even at a higher temperature [56–58]. Hence, there is a need to develop a catalyst with high TON at low temperature with high selectivity of acid production (See SI, Table S1). From the TON point of view of a heterogeneous catalyst, metal nanoparticles have gained importance due to their high catalytic activity with low particle size and high surface area [59–65]. In 2011, Hutchings et al. have reported [66] the oxidation of toluene with molecular oxygen as an oxidant using AuPd supported catalyst at 120–160 °C.

In literature, there are only very few reports available for the selective oxidation of toluene to benzoic acid using TBHP as oxidant at lower temperatures. Compared to other metal oxidants, TBHP is economic and avoids the formation of waste. Lingaiah et al. have reported vanadium substituted polyoxometalate catalysts for oxidation of toluene to benzaldehyde using TBHP as oxidant [67]. Hutchings et al. have used 1% Au-Pd/ $\text{TiO}_2$  for toluene oxidation to yield a mixture of products at 80 °C [68]. Alternatively, the platinum group metal catalysts are well known for the oxidation of hydrocarbons [69–75]. Recently, Shimizu and co-workers have reported a supported platinum catalyst for solvent free synthesis of ester from primary alcohols under  $\text{N}_2$  at 180 °C [76].

Our continuous efforts towards the metal nanoparticles catalyzed organic transformations, [77–81] here in we report binaphthyl backbone stabilized Pt-nanoparticles (Pt-BNP) as a catalyst for the selective oxidation of petroleum waste toluene to benzoic acid with high conversion and TON.

## 2. Experimental section

### 2.1. Catalyst preparation

The platinum nanoparticles were synthesized by two steps procedure. First, [1,1'-binaphthalene]-2,2'-diamine (BINAM) was diazotised using  $\text{HBF}_4$  and  $\text{NaNO}_2$ . Then, the diazonium salt was treated with  $\text{H}_2\text{PtCl}_6$  in acetonitrile, followed by reduction of Pt(IV) by  $\text{NaBH}_4$  which resulted in Pt nanoparticles (Scheme 1). Simultaneously, the heat generated from the reduction leads to the generation of binaphthyl radical which stabilizes the nanoparticles via strong Pt-C linkage. Different type of Pt-NPs with different stabilizers such as phenyl (Pt-PNP), 1-naphthyl (Pt-NNP) and 8-quinonyl (Pt-QNP) have been synthesized using the above mention procedure. The details experiment procedure for the synthesis of Pt-NPs is given in SI.

### 2.2. Characterization of catalyst

The formation of platinum nanoparticles was confirmed by UV spectroscopy using SHIMADZU UV-3100 spectrophotometer and quartz cuvette with a 10 mm path length. Size and shape of the Pt-NP was analyzed with (HR-TEM) JEOL-3010 transmission electron microscope operating at 300 kV, which showed the particle size in the range between 4–8 nm. Samples for HR-TEM were prepared by dispersing the

powdered sample in dichloromethane (DCM) by sonication and then drip drying on a copper grid (200 mesh) coated with carbon film. To determine the binaphthyl moieties present in the nanoparticles as stabilizer, FTIR analysis using Jasco FT/IR-4100 and solid state NMR data were obtained using high resolution 400 NMR (Bruker). The crystalline structure of the platinum nanoparticles was determined by X-ray diffraction analysis using D8 advance (Bruker) X-ray diffractometer instrument at room temperature. The latter appeared with Cu  $\text{K}\alpha$  (1.5406 Å) voltage: 40 kV, current: 30 mA and was in the range of 10–80 (2 $\theta$ ). All the peaks in PXRD pattern were assigned and compared with the database published by JCPDS. The X-ray photoelectron spectroscopy (XPS) was conducted on an XPS analysis (Omicron ESCA Probe spectrometer) equipped with monochromatic Mg  $\text{K}\alpha$  (1253.6 eV). The binding energy was calibrated using the C 1s photoelectron peak at 284.8 eV as a reference (see SI). The elemental composition in the reaction mixture was determined by EDX analysis. The quantity of Pt content (1.6 wt%) in nanoparticle was determined by ICP-OES analysis using Perkin Elmer Optima 5300 DV.

### 2.3. Catalytic reaction

Under open atmosphere, toluene 1 (0.5 mmol), 0.066 mol% (8 mg) of Pt-BNP (1.6 wt% Pt by ICP-OES analysis), 70% aqueous TBHP (2.0 mmol) and nanopure water (1.0 mL) were successively added to oven dried reaction tube then the reaction tube was fitted with oxygen balloon. Nano pure water was obtained from Barnstead nanopure water system. Then the reaction tube was immersed in an 80 °C pre-heated oil bath and stirred with a stir bar till complete consumption of toluene. Upon cooling down to room temperature, the reaction tube was washed with ethanol, and the liquid was added to the collection vial. The internal standard substance naphthalene was also added to the collection vial. The samples were analyzed by GC (Shimadzu GC-2010) equipped with FID and Stabilwax®-DA, capillary column (35 m, 0.32 mmID, 0.25  $\mu\text{m}$ ).

The conversion (%) of toluene was calculated using the standard procedure:

Conversion % of toluene

$$= \frac{(\text{Initial moles of toluene} - \text{moles of toluene remained after the reaction})}{(\text{initial moles of toluene for the reaction})} \times 100$$

The yield (%) of acid was calculated using this formula:

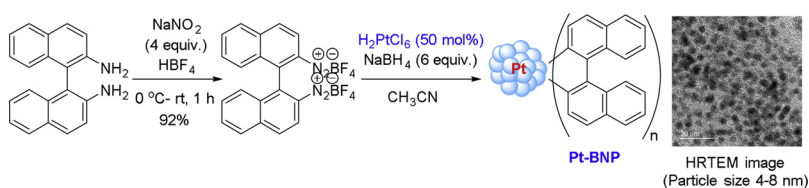
$$\% \text{yield of acid} = \frac{\text{moles of acid formed}}{\text{initial moles of toluene for the reaction}} \times 100.$$

The TON (turn over number) of catalyst was calculated using the formula:

$$\text{TON} = \frac{\text{mole of product formed}}{\text{mole of catalyst used for the reaction}}$$

### 2.4. Experimental procedure for reusing of Pt-BNP catalyst

To reuse the Pt-BNP catalyst, the reaction was repeated with 4-methoxy toluene 1a as a substrate in 1.0 mmol scale retaining identical conditions, except the usage of Pt-BNP catalyst rather than fresh catalyst. After the completion of 4-methoxy toluene oxidation reaction, the



Scheme 1. Synthesis of Pt nanoparticles (Pt-BNP).

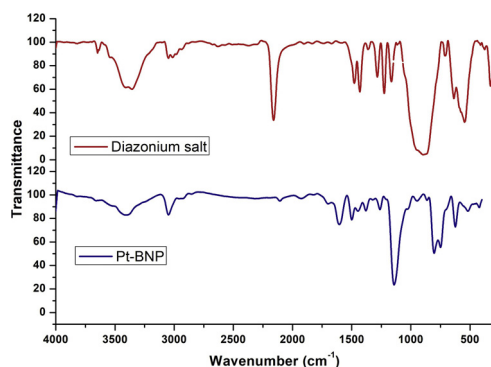


Fig. 1. IR spectrum of both BINAM diazonium salt and Pt-BNP.

reaction mixture was allowed to cool to room temperature. EtOH (2 mL) was added to the reaction mixture and centrifuged. The liquid was decanted to a 50 mL conical flask. Again EtOH (5 mL) was added and centrifuged and decanted to the same conical flask. This procedure was repeated up to three times. After that, the catalyst was washed with nano pure water (5 mL) and ethanol (5 mL) two times. Finally, the resulting solid residue (Pt-BNP) dried under vacuum. The dried catalyst was reused for further catalytic cycle. The collected liquid was concentrated by reduce pressure. The resulting reaction mixture was purified by column chromatography on silica gel (hexanes: ethyl acetate) to afford **4a** as the desired product.

### 3. Results and discussion

#### 3.1. Characterization of Pt-BNP

Inferences were drawn from the comparison of FTIR spectra of the Pt-binaphthyl NPs (Pt-BNP) with the corresponding BINAM diazonium salt. The absence of absorption band at  $2263\text{ cm}^{-1}$  in the Pt NPs indicated the absence of the diazonium group in the synthesized NPs (Fig. 1). The bands at  $3048\text{ cm}^{-1}$  and  $2925\text{ cm}^{-1}$  in Pt-BNPs corresponds to the stretching vibrations of aromatic C–H. The bands at 805, 751 and  $621\text{ cm}^{-1}$  are ascribed to C–H bending and peaks at 1600 and  $1505\text{ cm}^{-1}$  are because of C=C vibrations. All these data confirmed the presence of the binaphthyl moiety in the synthesized Pt-BNPs.

In UV–vis spectra, we found a peak at 278 nm correspond to the platinum nanoparticle. And peaks at 346 nm, 362 nm and 411 nm corresponding to organic aromatic binaphthyl stabilizer of NPs. The peak corresponds to the  $\text{H}_2\text{PtCl}_6$  and  $\text{PtCl}_4$  at 262 nm, 327 nm and 393 nm respectively are completely disappear from the NPs which shows that the platinum metal salt completely converted to NPs (Fig. 2).

Further  $^{195}\text{Pt}$  NMR study has been carried out for characterization of Pt-BNP. Two broad peaks were observed at  $-2769$  and  $-2346$  ppm in  $^{195}\text{Pt}$  NMR. The oxidation of platinum atom from lower Pt(0) to higher

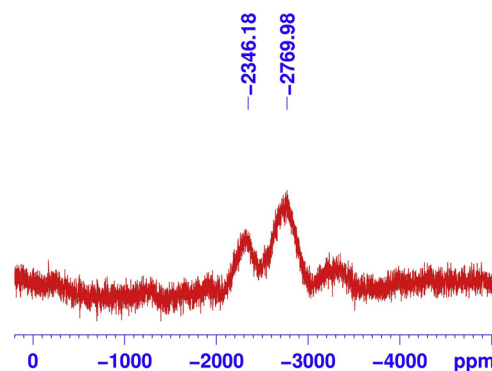


Fig. 3.  $^{195}\text{Pt}$  NMR of Pt-BNP in  $\text{CDCl}_3$  (107 MHz).

Pt(II) changes by removal of electrons, it leads to deshielding and thus, high-frequency shifts are observed. [82] When the binaphthyl moiety binds on the surface atom of NPs through covalent bond, the binaphthyl binding metal atom attains to the higher oxidation state. That may be the reason for two broad peaks at  $-2769$  and  $-2346$  ppm in  $^{195}\text{Pt}$  NMR. The intensity of peak at  $-2346$  ppm is lower compared to the peak at  $-2769$  ppm which indicates that less number of Pt atom may bind with binaphthyl moiety. There are no peaks corresponding to the  $\text{H}_2\text{PtCl}_6$  and  $\text{PtCl}_4$  complex, which shows that the platinum salts are completely converted to the Pt-NPs during the preparation of NPs (Fig. 3).

The crystalline nature of Pt-BNP has proved from powder XRD data. In powder XRD pattern of Pt-BNP, peaks found at  $31.9$ ,  $33.9$ ,  $39.8$ ,  $45.1$ ,  $45.9$ ,  $67.4$  and  $81.6$  which corresponds to peak  $\text{Pt}_3\text{O}_4$  (100), PtO (101), Pt (111), PtO (102), Pt (200), Pt (220) and Pt (311) respectively (JCPDS number are 751060, 850714 and 882343) (Fig. 4). Latter using the Debye-Scherrer equation from P-XRD calculated the particle size of Pt-BNP, the average particle size is 7.0 nm (See SI). The result quite agrees with HRTEM analysis data of particle size.

HRTEM images of Pt NPs revealed that most of the particles are spherical in shape and are well dispersed on the TEM grid without any apparent aggregation. The Pt NPs have a particles size distribution of 4–8 nm (Fig. 5). High resolution TEM images divulged a well-defined lattice fringe of 0.20 nm which is accredited to the lattice plane (Fig. 6).

The oxidation state of Pt atom in Pt-BNP was confirmed by XPS analysis. The XPS investigation of Pt 4f region (Pt  $4f_{7/2}$  and Pt  $4f_{5/2}$ ) revealed that the binding energy values for Pt  $4f_{7/2}$  and Pt  $4f_{5/2}$  lines in Pt nanoparticle core are 71.0 and 74.4 compared with pure platinum metal. The binding energy of  $\text{Pt}^{2+} 4f_{7/2}$  and  $\text{Pt}^{2+} 4f_{5/2}$  found at 73.9 and 77.2 respectively. From the spectrum (Fig. 7), it was observed that the NPs were present in  $\text{Pt}^0$ ,  $\text{Pt}^{2+}$  and  $\text{Pt}^{4+}$  oxidation state and ratio was found 47, 36 and 17 respectively. Surface oxidation of Pt to PtO and  $\text{PtO}_2$  could be a possible justification to this. In addition, some of the Pt atoms may bond to binaphthyl moieties and resulted in  $\text{Pt}^{2+}$  oxidation

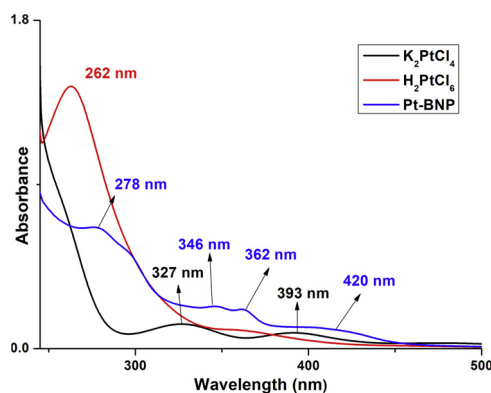


Fig. 2. UV–vis spectrum of Pt-BNP.

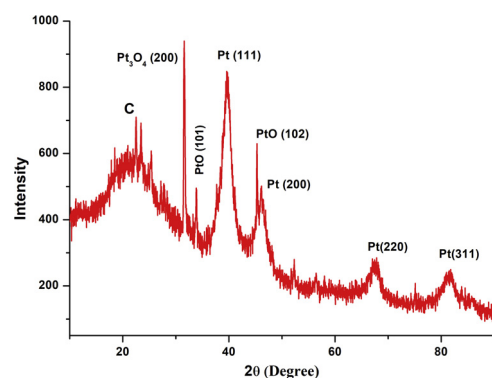


Fig. 4. The powder XRD pattern of Pt-BNP.

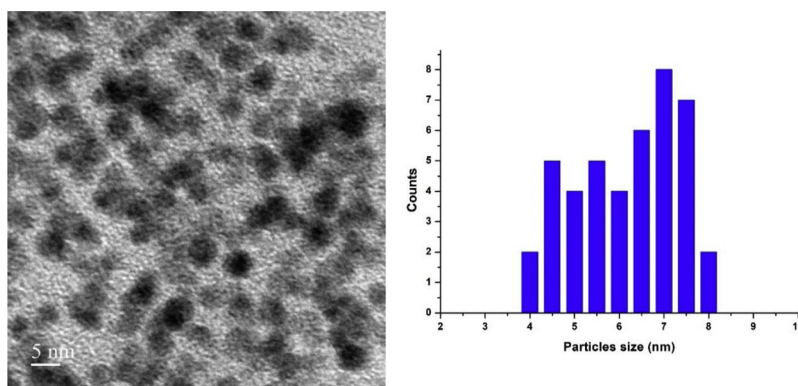


Fig. 5. Depicts the HR-TEM micrographs of Pt-BNP and particle size distribution.

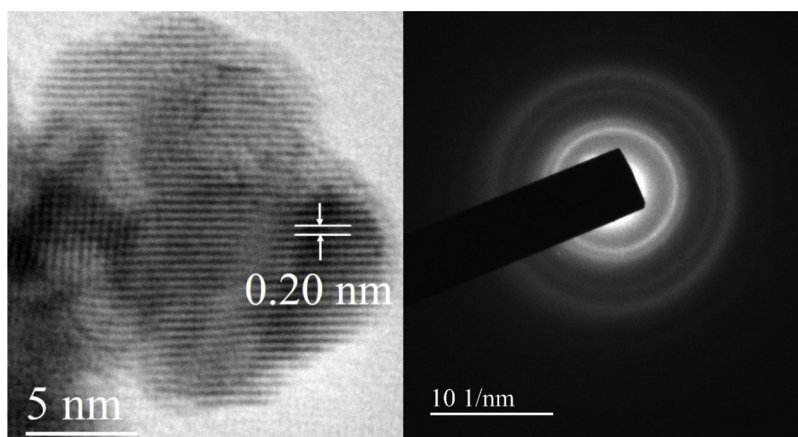


Fig. 6. High-resolution TEM image with defined lattice fringe.

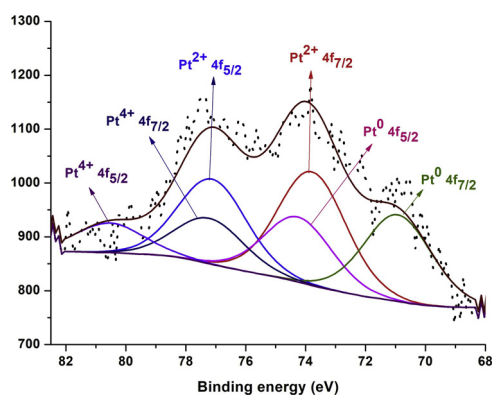


Fig. 7. XPS spectrum of Pt-BNP.

state.

### 3.2. Oxidation of toluenes

After detailed characterization of synthesized Pt-BNP, it was used as catalyst for oxidation of toluene. The initial investigation was carried out by using 4-methoxy toluene (**1a**) as a model substrate in presence of Pt-BNP (8 mg) catalyst and molecular oxygen as oxidant at 60 °C under solvent-free condition. It was observed that the reaction did not proceed; starting material remained as it is. But, when the reaction was carried out using TBHP as oxidant in water as solvent, it gave 61% yield of corresponding *p*-anisic acid selectively as sole product (Table 1, entry 1). Stimulated by this initial result, the catalytic activity of other stabilized Pt-NP for this toluene oxidation was investigated. Other

Table 1

Pt NPs catalyzed oxidation of toluene.

$  \begin{array}{c}  \text{CH}_3 \\    \\  \text{H}_3\text{C}-\text{C}_6\text{H}_4-\text{O}-\text{CH}_3 \\  \text{1a}  \end{array}  \xrightarrow[\text{24 h}]{\text{Pt-NP (0.064 mol\%), 70\% aq. TBHP (4 equiv.)}, \text{H}_2\text{O}, 60^\circ\text{C}}  \begin{array}{c}  \text{CH}_2\text{OH} \\    \\  \text{H}_3\text{C}-\text{C}_6\text{H}_4-\text{O}-\text{CH}_3 \\  \text{2a}  \end{array}  +  \begin{array}{c}  \text{CHO} \\    \\  \text{H}_3\text{C}-\text{C}_6\text{H}_4-\text{O}-\text{CH}_3 \\  \text{3a}  \end{array}  +  \begin{array}{c}  \text{COOH} \\    \\  \text{H}_3\text{C}-\text{C}_6\text{H}_4-\text{O}-\text{CH}_3 \\  \text{4a}  \end{array}  $			
Nanoparticles	Yield (%) <b>2a/3a/4a</b>	Nanoparticles	Yield (%) <b>2a/3a/4a</b>
 Pt-BNP	1/0/61	 Pt-NNP	1/1/53
 Pt-DPNP	1/2/48	 Pt-QNP	2/0/57

nanoparticles stabilizers such as phenyl (Pt-PNP), 1-naphthyl (Pt-NNP), and 8-quinonyl (Pt-QNP) have been used to improve the yield of the process. However, these NPs showed only low to moderate activities compared with Pt-BNP. Notably, the homogeneous platinum salts  $\text{PtCl}_2$  and  $\text{K}_2\text{PtCl}_4$  were investigated for the oxidation reaction and they were unable to oxidize the 4-methyl anisole. Further optimization of reaction parameters was studied using Pt-BNP as catalyst and TBHP as an oxidant.

Then, the effect of Pt-BNP catalyst loading for oxidation of 4-methyl anisole to 4-anisic acid was investigated and the results are summarized



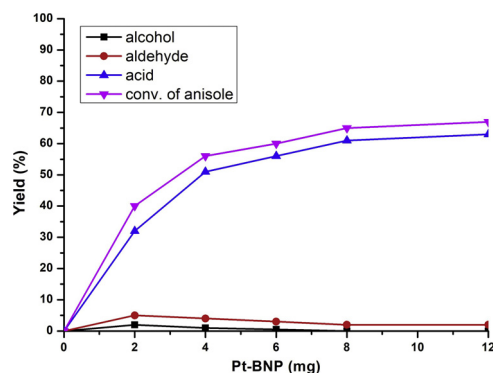


Fig. 8. Pt-BNP catalyst loading effect in toluene oxidation.

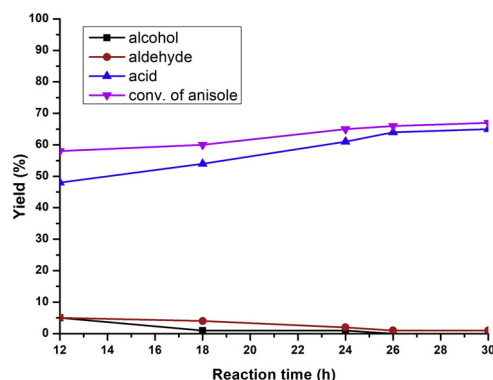


Fig. 9. Effect of reaction time on oxidation of 4-methoxy toluene.

in Fig. 8. Decreasing the catalyst loading from 8 mg (0.064) to 2 mg (0.017 mol%), decreased both the conversion (40%) and formation of the corresponding acid (32%) simultaneously. On further increasing the catalyst loading from 8 mg (0.064) to 12 mg (0.1), the yield of the acid did not increase significantly. In the absence of the catalyst, no product formation was observed.

To improve the yield of acid, further optimization was carried out using 8 mg of Pt-BNP catalyst. Subsequently, the reaction time was investigated. After 26 h, yield and conversion did not increase significantly, this may be due to the lack of oxidant present in the reaction

**Table 3**  
Optimization of reaction in oxygen atmosphere<sup>a</sup>.

Entry	Oxidant (equiv.)	Temp. (°C)	Yield (%) <sup>b</sup> 2a	Yield (%) <sup>b</sup> 3a	Yield (%) <sup>b</sup> 4a
1	TBHP (4.0)/ O <sub>2</sub>	60	0.0	3.5	70.0
2	TBHP (2.0)/ O <sub>2</sub>	60	0.0	2.9	65.0
3	TBHP (2.0)/ O <sub>2</sub>	70	0.4	0.8	89.0
4	<b>TBHP (2.0)/ O<sub>2</sub></b>	<b>80</b>	<b>0.0</b>	<b>0.0</b>	<b>95.0</b>
5	TBHP (1.0)/ O <sub>2</sub>	80	0.0	8.0	45.0
6	TBHP (0.5)/ O <sub>2</sub>	80	0.0	3.0	43.0

<sup>a</sup> Reaction conditions: **1a** (0.5 mmol), 70% aqueous TBHP with 2 mL solvent in 26 h.

<sup>b</sup> Yield was calculated by GC.

mixture. Initially, the reaction generated alcohol which is immediately oxidized to corresponding aldehyde, and finally, the aldehyde was oxidized to acid (Fig. 9).

Then different types of oxidants were used to improve the yield. Except for TBHP, other oxidants such as molecular oxygen, K<sub>2</sub>S<sub>2</sub>O<sub>8</sub>, Na<sub>2</sub>S<sub>2</sub>O<sub>8</sub>, oxone and H<sub>2</sub>O<sub>2</sub> were unable to improve the yield of the acid (Table 2, entries 1–5). Then, the reaction was carried out in different solvents such as DCE, DMF, DMSO and THF which were failed to give the acid. The above solvent screening showed that the greener solvent water is the best for the oxidation of 4-methoxy toluene.

The TBHP itself good enough oxidant for conversion of toluene to benzoic acid but the requirement of a large quantity of TBHP which is not economically favourable. To reduce the quantity of TBHP, O<sub>2</sub> has been used for the oxidation of toluene. Surprisingly, when the reaction was carried out under oxygen atmosphere along with TBHP, the yield of acid increased to 70% (Table 3 and entry 1). In the presence of metal, molecular oxygen itself is a good oxidizing agent for oxidation of aldehyde to acid. So the reaction was carried out in the presence of 2 equivalents of TBHP in oxygen atmosphere. As expected, not much variation in yield was observed (entry 2).

Further, the reaction temperature was increased to improve the yield of acid. When the reaction was carried out at 80 °C, the maximum

**Table 2**  
Optimization of reaction parameters<sup>a</sup>.

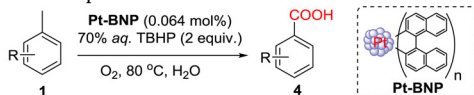
Entry	Catalyst	Oxidant	Solvent	Yield (%) <sup>b</sup> 2a	Yield (%) <sup>b</sup> 3a	Yield (%) <sup>b</sup> 4a
1	Pt-BNP	O <sub>2</sub>	H <sub>2</sub> O	0.0	0.0	0.0
2	Pt-BNP	K <sub>2</sub> S <sub>2</sub> O <sub>8</sub>	H <sub>2</sub> O	0.0	0.0	0.0
3	Pt-BNP	Na <sub>2</sub> S <sub>2</sub> O <sub>8</sub>	H <sub>2</sub> O	0.0	0.0	0.0
4	Pt-BNP	Oxone	H <sub>2</sub> O	0.0	0.0	0.0
5	Pt-BNP	H <sub>2</sub> O <sub>2</sub>	H <sub>2</sub> O	0.0	0.0	0.0
6 <sup>c</sup>	Pt-BNP	TBHP	–	3.5	3.3	39.0
7	Pt-BNP	TBHP	EtOH	1.1	12.0	18.0
8	Pt-BNP	TBHP	MeOH	2.0	10.0	20.0
9	Pt-BNP	TBHP	THF	0.0	0.0	0.0
10	Pt-BNP	TBHP	DMF	0.0	0.0	0.0
11	Pt-BNP	TBHP	DMSO	0.0	0.0	0.0

<sup>a</sup> Reaction conditions: **1a** (0.5 mmol), 70% aqueous TBHP with 2 mL of solvent in 26 h.

<sup>b</sup> Yield was calculated by GC.

<sup>c</sup> 5.0 M TBHP in decane was used.

**Table 4**  
Substrate scope with electron rich and neutral toluenes<sup>a</sup>.



Entry	Toluenes	Product	Time (h)	Yield (%)
1			26	95
2			26	86
3			26	79
4			26	75
5			28	81
6			26	92
7			26	95

<sup>a</sup> Reaction was carried out in 1.0 mmol scale.

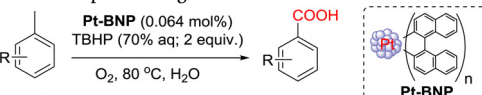
yield was observed as 95% (entry 4). Further reducing the TBHP equivalent was ineffective to increase the yield of acid (entries 5 and 6). So the optimized reaction condition was found to be Pt-BNP (8 mg), TBHP (2 equiv.) under oxygen atmosphere at 80 °C for 26 h.

With this optimized reaction condition in hand, various substituted toluenes were oxidized to corresponding acids and the results are summarized in Tables 4, 5 and 6. Both electron donating and electron withdrawing group substituted toluenes were oxidized to corresponding acids under the optimized condition. The electron rich toluenes took shorter reaction time compared to electron deficient toluene which indicates that electron donating group containing toluene are more active substrates for the oxidation reaction. Electron donating group such as OMe and Me substituted toluene gave a very good yield of acid products (Table 4 and entries 1–4). Electronically neutral substrate such as 1-methyl naphthalene and toluene underwent the optimized reaction condition and yielded the corresponding product **4f** and **4g** in 92 and 95%, respectively.

Interestingly, halogens such as chloro, bromo and iodo substituted toluene underwent to this oxidation smoothly without affecting halogen group and gave the corresponding acid product in very good yield (Table 5). This halo acid can be utilized for further organic transformations. In the case of 3-chloro toluene, 87% yield of acid **4h** was observed. Both *ortho* and *para*-substituted bromo toluene gave 89% and 90% yields of **4i** and **4j** respectively. The 4-iodotoluene gave less yield compared to 3-iodotoluene, the reason may be the insoluble nature of solid 4-iodotoluene (entries 4 and 5).

In general, oxidation of electron withdrawing group containing toluene is very difficult and there is a need to apply harsh reaction conditions for smooth conversion. The optimized reaction condition was

**Table 5**  
Substrate scope of halogen substituted toluenes<sup>a</sup>.



Entry	Toluenes	Product	Time (h)	Yield (%)
1			29	87
2			30	89
3			30	90
4			24	91
5			32	77

<sup>a</sup> Reaction was carried out in 1.0 mmol scale.

applied to electron deficient substrate, and it took longer reaction time compared to the electron rich system. The mild electron withdrawing group containing toluenes gave very good yield of the corresponding acid. Interestingly, ester and acyl substituted toluenes gave the corresponding acid products under the optimized reaction condition in very good yield without affecting the ester and the acyl group (Table 6, entries 1–3).

Highly electron deficient system such as 4-nitro toluene took longer reaction time of 48 h and yield of product **4q** was also less. The methyl substituted heteroaromatic compounds gave low yield of acid product (entries 5–8).

From the substrate scope, it has been observed that the electron rich toluenes afford excellent yields over electron deficient toluenes. Further, a competitive reaction was carried out using 1:1 ratio of para-methoxy toluene and para-nitro toluene. The results obtained shows that an electron rich toluene reacted faster and gave excellent yield of product, whereas electron deficient toluene performed poorly and afforded the less yield of product (Table 7, entry 1). When the TBHP equivalent was changed from 4 to 2 equivalents, electron rich toluene consumed faster and gave the corresponding acid product in good yield, whereas electron deficient toluene was consumed very slowly and gave only 2% yield of corresponding acid (entry 2).

To ensure the practical utility of the optimized reaction condition, a gram scale reaction was performed using 4-methoxy toluene (**1a**) which afforded promising 91% yield of the corresponding 4-methoxy benzoic acid (**4a**) (Scheme 2).

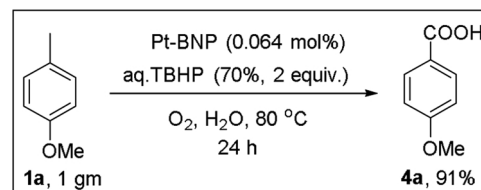
Next, an attempt was made to synthesize industrially important chemical terephthalic acid from xylene by increasing the equivalents of oxidant. When 4 equivalents of TBHP was used at a time, it gave only 7% yield (Table 8, entry 1) of p-terephthalic acid, but two portion wise addition of TBHP at 26 h intervals gave 22% yield of p-terephthalic acid as the solubility of intermediate product p-toluic acid in water is low (entry 2). Then mixed solvent (water and AcOH (1:1)) was used to solubilise the intermediate product p-toluic acid and the reaction gave

**Table 6**

Substrate scope with electron deficient toluene and heteroaromatic system.

Entry	Toluenes	Product	Time (h)	Yield (%)
1			28	93
2			28	96
3			30	86
4			48	68
5 <sup>a</sup>			48	47
6 <sup>a</sup>			48	60
7 <sup>a</sup>			48	65
8 <sup>a</sup>			48	58

<sup>a</sup> Yield was calculated by GC using naphthalene as internal standard.

**Scheme 2.** A gram scale reaction of Pt-BNP catalyzed oxidation.**Table 8**

oxidation of xylene to terephthalic acid.

Entry	Solvent	Conversion (%)	Yield (%)	
			4c	4cc
1	H <sub>2</sub> O	> 99	86	7
2 <sup>a</sup>	H <sub>2</sub> O	> 99	70	22
3 <sup>a</sup>	H <sub>2</sub> O:AcOH(1:1)	> 99	39	52

<sup>a</sup> TBHP was added at 26 h intervals in two portion.

52% yield of p-terephthalic acid (Table 8, entry 3).

During the study of the substrate scope, it has been shown that the acyl group is well tolerated under the optimized reaction condition. Next, attempts were made to synthesize keto compound from corresponding alkyl benzene and the results are summarized in Table 9. It was found that both acyclic and cyclic system afforded the corresponding ketone in very good yields. Ethylbenzene gave 94% of corresponding acetophenone (6a), (entry 1). Propylbenzene afforded the corresponding propiophenone (6b) in 96% yield (entry 2) and cyclic system indane yielded corresponding indanone (6c) in 89% (entry 3). As expected the 4-ethylphenol undergoes radical polymerization under the optimized reaction condition and unable to give corresponding 4-acylphenol (6d) (entry 4). However, the phenylacetic acid was unable to afford the  $\alpha$ -keto acid (6e) (entry 5).

Interestingly, methyl ester of phenylacetic acid 5e gave the corresponding  $\alpha$ -keto ester (6f) (entry 6) in very good yield. Further, various phenylacetic acid ester has been used for the synthesis of corresponding  $\alpha$ -keto ester molecules. Halogen substituted such as *ortho* bromo (5g) and *para* bromo (5h) methyl ester of phenylacetic acid yielded the corresponding  $\alpha$ -keto ester (6g and 6h) in 81 and 84% respectively. Isopropyl ester of phenylacetic acid gave good yield of corresponding corresponding  $\alpha$ -keto ester 6i under the optimized reaction condition.

For the practical utilization of present methodology, a gram scale reaction was carried out using ethylbenzene as a substrate without

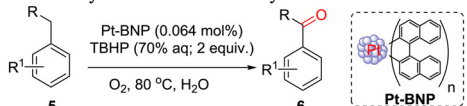
**Table 7**

competitive experiment with respect to electron rich and deficient toluene.

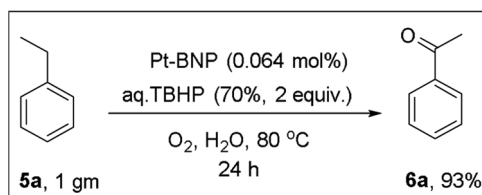
Entry	TBHP (x equiv.)	Yield (%)							
		4a	3a	2a	1a	4p	3p	2p	1p
1	4	94	1	1	0	34	2	0	60
2	2	87	2	1	3	2	1	0	94

**Table 9**

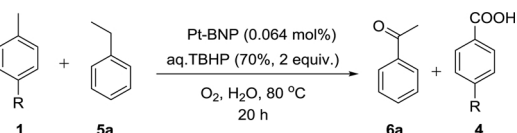
Pt-BNP catalyzed oxidation of alkyl benzene to aromatic ketone.



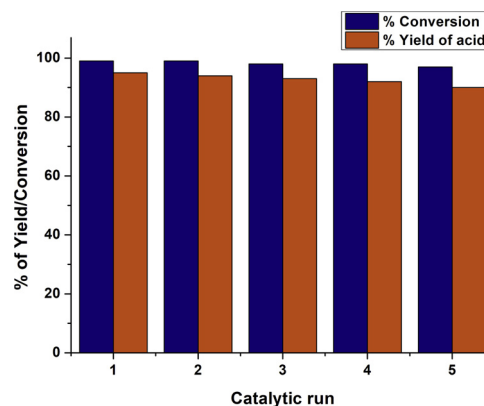
Entry	Reactant	Product	Time (h)	Yield (%)
1			20	94
2			20	98
3			24	89
4			24	00
5			48	00
6			18	87
7			20	81
8			20	84
9			20	80

**Scheme 3.** A gram scale reaction of Pt-BNP catalyzed oxidation of ethyl benzene.**Table 10**

competitive experiment with respect to electron rich/neutral toluene and ethylbenzene.



Entry	Toluene	Alkyl benzene	Conversion (%)		Yield (%)	
			1	5a	4	6a
1	1a	5a	48	50	41	46
2	1g	5a	24	77	19	65

**Fig. 10.** Recyclability test of Pt-BNP catalyst.

compromising the optimized reaction condition and gave 93% yield of corresponding acetophenone (Scheme 3).

For our curiosity, a competitive experiment was carried out by using 1:1 ratio of electron rich para-methoxy toluene and ethylbenzene, and the results showed (Table 10, entry 1) that both the starting material have similar reactivity as the reaction gave 46% of acetophenone and 41% of 4-methoxy benzoic acid. However, a competitive experiment between electrically neutral substrate such as toluene and ethylbenzene suggested that benzylic  $\text{CH}_2$  is oxidized faster than the benzylic  $\text{CH}_3$  (entry 2).

### 3.3. Stability of catalyst in the reaction medium

From the economical viewpoint, further efforts were made to recover and reuse the Pt-BNP catalyst. The toluene oxidation reaction was carried out at 1 mmol scale under the optimized conditions. The catalyst was recovered and reused up to five catalytic cycles and desired product **4a** was isolated in the 95%, 93%, 94%, 92% and 90% yields in successive runs. The recovery (%) of Pt-BNP in each run was calculated with respect to previous run. In every run, there are some weight loss of catalyst was observed, it may the loss of catalyst during the decantation. This result reveals that the catalytic activity remains the same as initial stage catalysts (Fig. 10).

Moreover, HRTEM analysis of recovered Pt-BNP catalyst after five runs showed that there was no major change in the size distribution and dispersion of the nanoparticles compared with the freshly prepared catalyst. The average size of Pt-BNP was found to be 5–8 nm (Fig. 11).

To prove that the active species of Pt-BNP catalyst is heterogeneous Pt, not the leached homogeneous Pt species, the heterogeneous test such as hot centrifugation test and the mercury poisoning test were carried out. In hot centrifugation test, the reaction mixture was filtered in the middle of the reaction at different time intervals, 6 h, 12 h and 18 h respectively. Then the filtrate was allowed to stir for next 30 h. It was observed that the reaction did not proceed with the filtrate. The



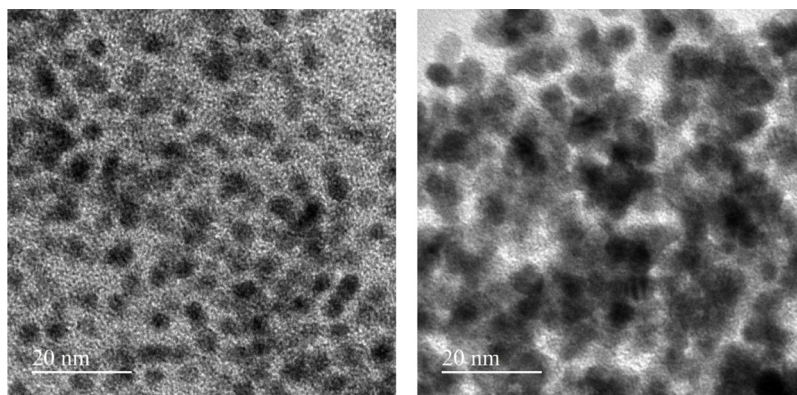


Fig. 11. HRTEM image of Pt-BNP catalyst: Fresh catalyst (left) and recycled catalyst after five runs (right).

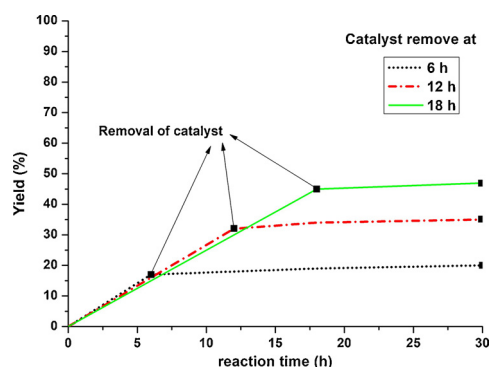
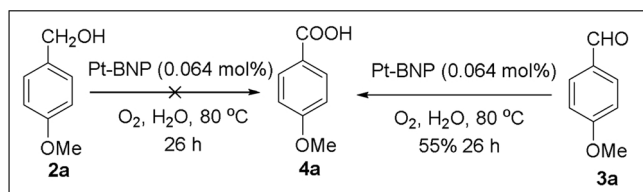
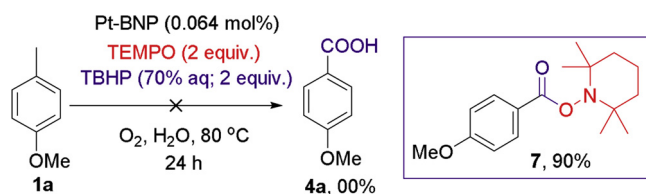


Fig. 12. Graphical representation of hot centrifugation test.



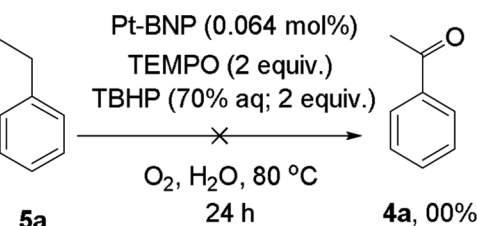
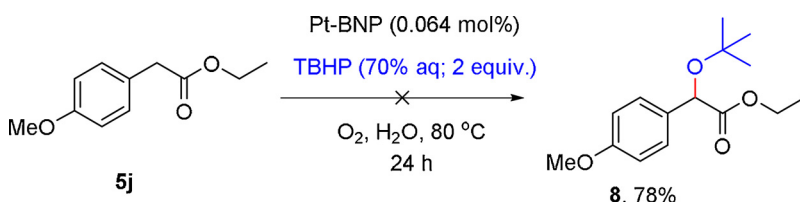
Scheme 4. Control experiments in absence of TBHP.



Scheme 5. Free radical trapping experiment in presence of TEMPO.

catalytic activity of residue Pt-BNP after hot filtration was similar to fresh Pt-BNP (Fig. 12).

Then, the mercury poisoning test was conducted, and results show that the Pt-BNP is heterogeneous nature in reaction medium.



Scheme 7. Ethyl benzene oxidation in presence of TEMPO.

### 3.4. Reaction mechanism

To get an insight in to the mechanism of the reaction, few control experiments were carried out. In literature, aerobic oxidation of aldehyde to corresponding acid in absence of TBHP is well-known. As expected, when the aldehyde oxidation was carried out under the standard reaction condition without TBHP, it yielded the corresponding acid in 55% (Scheme 4). However, when the same condition was applied for the oxidation of alcohol, it did not give any yield of acid, and the starting material was recovered as it is. This result indicates that the Pt-BNP and molecular oxygen is good enough for oxidation of aldehyde to acid.

To confirm whether the reaction proceeds via ionic or free radical pathway, a reaction was carried out in presence of TEMPO (2,2,6,6-Tetramethyl-1-piperidinyloxy) as free radical trapping agent. In presence of TEMPO, the reaction did not yield the corresponding acid, and it gave the corresponding TEMPO adduct 7 with acyl radical in 90% (Scheme 5). This result proves that the reaction may proceed via free radical path way.

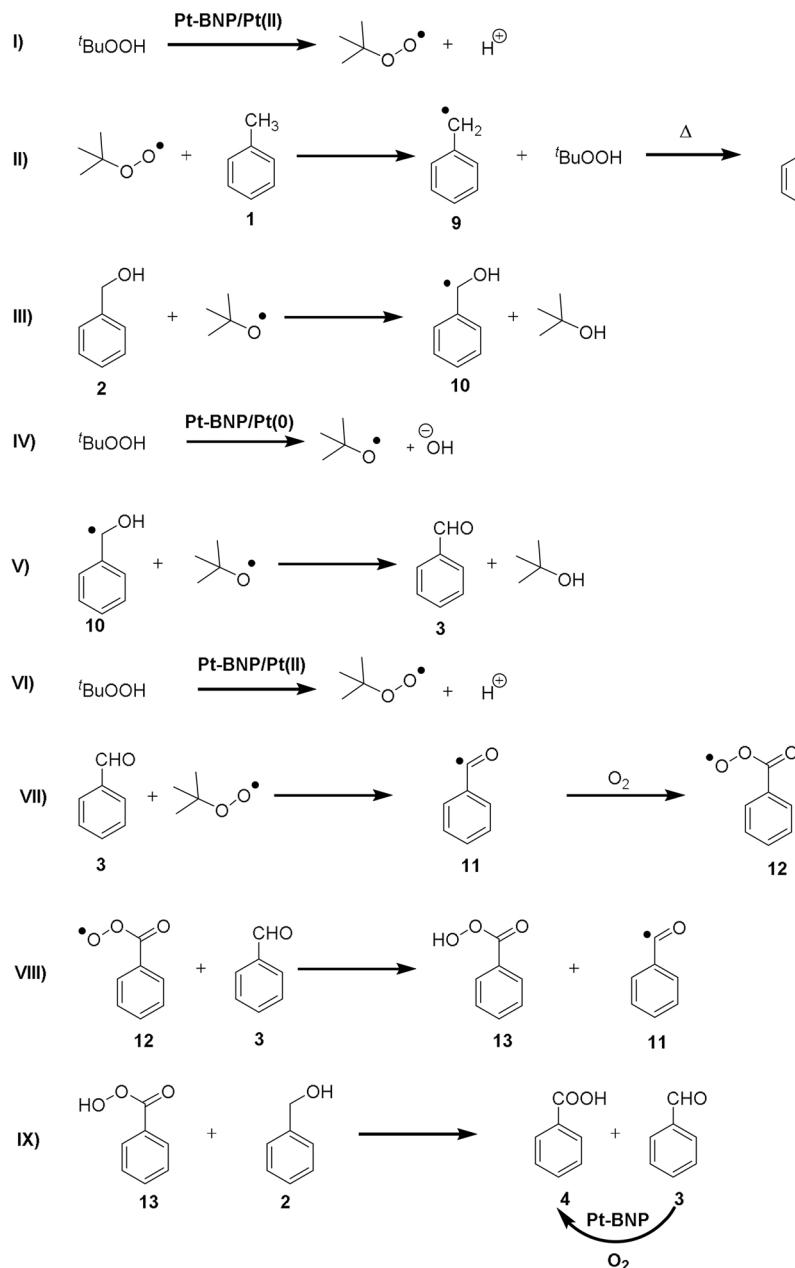
When the reaction was carried out by using ethyl 2-(4-methoxyphenyl)acetate as a substrate, we were able to isolate the corresponding tertiary butoxide adduct intermediate 8 in 78% yield (Scheme 6). The intermediate 8 was confirmed by <sup>1</sup>H-NMR, <sup>13</sup>C-NMR and HRMS analysis (See SI). Further, the reaction was carried out in presence of TEMPO and the reaction did not take place (Scheme 7) which suggested that the oxidation of alkylarenes proceed via free radical pathway.

In presence of metal, TBHP can decompose via two pathways depending on the oxidation state of metal (Scheme 8). Generally, in presence of higher oxidation state of metal, TBHP generates tertiary

Scheme 6. Tertiary butoxide intermediate trapping experiment.

$M(\text{higher oxidation}) + t\text{-Bu-O-OH} \longrightarrow M(\text{Lower oxidation}) + t\text{-BuOO}^\bullet + \text{H}^+$  **Scheme 8.** Decomposition of TBHP in presence of metal.

$M(\text{lower oxidation}) + t\text{-Bu-O-OH} \longrightarrow M(\text{Higher oxidation}) + t\text{-BuO}^\bullet + \bar{\text{O}}\text{H}$



**Scheme 9.** Possible reaction mechanism.

butoxide radical whereas in the lower oxidation state of metal generates tertiary butyl peroxide radical [83].

The oxidation of aldehyde to benzoic acid may proceed via a different pathway with complex reaction mechanism. However, based on literature reports and above control experiments, a possible reaction mechanism is proposed (Scheme 9). First, in presence of TBHP, benzyl radical **9** is generated which reacts with hydroxyl radical and give the benzyl alcohol **2** (equation II). The hydroxyl group of benzyl alcohol comes from TBHP. At the time of formation of benzyl alcohol, TBHP decomposes to corresponding tertiary butoxide radical. Then tertiary butoxide radical abstract hydrogen radical from benzyl alcohol and immediately generate tertiary butanol and benzyl alcohol radical **10**

(equation III) which is further oxidized to corresponding aldehyde **3** (equation V). The formation of benzyl alcohol and benzaldehyde during the reaction was confirmed by GC–MS analysis of reaction mixture (See Fig. 2). Then benzoyl radical **11** is generated, in presence of TBHP from benzaldehyde **3**. However, the possibility to generate benzoyl radical in presence of metal and molecular oxygen cannot be ruled out. Further, in presence of molecular oxygen, benzoyl radical gets converted to corresponding benzyl peroxy radical **12** intermediate (equation VII). The benzoylperoxy radical takes hydrogen from benzaldehyde and generates peroxy benzoic acid **13** and benzoyl radical **11** (equation VIII). Subsequently, peroxy benzoic acid generates the benzoic acid **4** (equation IX). There is another possibility to produce benzoic acid from

benzoyl radical, the benzoyl radical in presence of Pt-BNP react with hydroxyl ion and produce the corresponding acid molecule (Scheme 9). The possibility of oxidation of aldehyde to acid by TBHP cannot be ruled out. However, the actual oxidation state of Pt-BNP involved in oxidation reaction is not confirmed as Pt-BNP contain Pt(0), Pt(II) and Pt(IV).

#### 4. Conclusion

An efficient method for Pt-BNP catalyzed sequential selective oxidation of methyl and alkylarenes to corresponding carboxylic acid and ketone with high conversion under mild reaction condition has been developed. This methodology has been successfully utilized for the oxidation of less reactive electron deficient toluenes to the corresponding acid. In this methodology, easily accessible petroleum by-product toluene, and greener oxidant TBHP were used for the oxidation. The toluene oxidation reaction has proceeded in presence of 0.064 mol % of Pt-BNP catalyst in water. The synthesized Pt-BNP catalyst has shown high TON (738–1448) for selective oxidation of toluene to benzoic acid. The Pt-BNP catalyst was reused up to six catalytic cycles without any major change in particle size and activity. Mercury poisoning test and hot centrifugation test confirmed that the reaction is catalyzed by heterogeneous Pt-BNP and not by leached homogeneous Pt.

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#### Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:<https://doi.org/10.1016/j.apcatb.2019.03.052>.

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